# Comparison of Soil Physical Properties under Two Different Water Table Management Regimes

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## ABSTRACT

**Soil physical properties are important indicators of the potential for agricultural production. The objective of this research was to examine the difference in soil physical properties 9 yr after the initiation of two water table management (WTM) treatments in Wood County, Ohio. Water table management treatments included both unrestricted subsurface drainage year round (Drainage Treatment) and subirrigation during the crop-growing season to maintain the water table at 25 cm below the surface with unrestricted subsurface drainage the remainder of the year (Subirrigation Treatment). Soil samples were collected in eight plots, in six depth increments to a 1-m depth. Soil aggregation and related properties were significantly different in response to WTM treatments and soil depths. The subirrigated treatment had lower aggregate stability at 40 to 50 cm compared with the drainage treatment. The mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates in the subirrigated treatment were smaller than the drainage treatment at depths of 30 to 75 cm. Percentage of macroaggregates and aggregate ratios were generally lower in the subirrigation treatment than the drainage treatment. Subirrigated soils exhibited relatively lower bulk density with an associated increase in total porosity. The drainage treatment had greater penetration resistance from 30 to 45 cm on readings taken in Spring 2000. Subirrigated soils retained a greater volume of moisture at all matric potentials except −0.00015 and −1.5 MPa. The subirrigated soils are apparently not able to develop large, stable aggregates as seen in the continuously drained soil, perhaps because of the frequent water saturation followed by slaking of soil macroaggregates associated with subirrigation.**

Water table management practices include surface drainage, subsurface drainage, controlled drainage, and subirrigation or a combination of these. These practices are utilized to remove excess water from on and within the soil. Subsurface drainage, the installation of perforated pipes at the 1- to 1.5-m depth in the soil, is the most common method of WTM in the Midwest USA with more than one third of the farms relying on subsurface drainage to improve their soil for crop production (Spillman, 2002). Controlled drainage restricts the outflow of water from subsurface drainage to a management-determined level; drainage only occurs when the water table rises above the management-determined level or when the control level is lowered. Subirrigation is the addition of water to the soil through the drain lines combined with restricted outflow of drainage water to prevent crops grown on drained soils from experiencing deficit water stress. Controlled drainage and subsurface drainage systems can often be retrofitted to function as a subirrigation system (Broughton, 1995). The use of WTM can alter the hydrological regime of the soil thus potentially altering the soil physical properties.

Soil physical properties improved, with respect to crop production characteristics, when the soil moisture content was decreased (Caron et al., 1992, Hermawan and Bomke, 1996). Soil bulk density ($\rho_b$), an important determinant of a soil's potential to support plant growth, can be affected by drainage. Soils with high bulk densities may restrict root growth, water movement, nutrient uptake, and gas exchange thus reducing crop productivity. Subirrigated and subsurface drained soils, when compared with undrained soils, have been reported to have lower $\rho_b$ in British Columbia, Canada (Chieng and Hughes-Games, 1995). Drained soils in Ohio have also been reported to have less dense surface crusts than undrained soils (Hundal et al., 1976), while another study in Ohio has reported no difference in the $\rho_b$ of the surface soil of drained and undrained soils (Lal and Fausey, 1993).

Drainage increases the macroporosity of the soil as well. Hundal et al. (1976) reported that soils with subsurface drainage had a greater volume of air-filled pores than undrained soils at matric potentials ranging from 0 to −0.1 MPa, suggesting that the drained soils had a larger number of macropores. In a more recent study, researchers found a decrease in macroporosity with the use of subirrigation compared with subsurface drainage (Chieng and Hughes-Games, 1995). They also reported that the closer the water table was maintained to the surface of the soil the fewer the number of macropores (Chieng and Hughes-Games, 1995).

Soil structure is also affected by altering the water table. Hooghouldt (1952), after 5 yr of WTM, reported differences in the structure between the surface layers of subirrigated and subsurface drained soils. The subirrigated soil was reported to be "…wetter and tough" making tillage more difficult (Van Hoorn, 1958). The temporal changes in soil structure were evidenced by a shift in the pore-size distribution in the subirrigated soil from macropores to micropores. Therefore, the author concluded that the deterioration of the soil structure might have been due to the change in the soil/water/air ratios. Throughout the length of the study, the percentage of soil air decreased in the subirrigated treatment (Van Hoorn, 1958).

While subsurface drainage remains the most commonly used WTM practice, subirrigation has recently been adopted as a means to enhance production and ad-

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Published in Soil Sci. Soc. Am. J. 68:1973–1981 (2004).

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**Abbreviations:** AWC, available water capacity; GMD, geometric mean diameter; MWD, mean weight diameter; $\rho_b$, soil bulk density; $\phi_t$, total porosity; WTM, water table management.

dress the environmental concerns associated with subsurface drainage. Subirrigation increases yields of corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] in the midwestern USA by reducing the amount of time crops experience deficit moisture stress (Fausey and Cooper, 1995; Fausey, 1994). Subirrigated soybean yields have been reported to average 1780 kg ha$^{-1}$ greater than subsurface drained soybean yields (Fausey and Cooper, 1995) Corn yields were reported to increase 45% in Ohio, in 1993, (a dry year) when subirrigated (Fausey, 1994).

While enhanced production is one important benefit of subirrigation, a second benefit of subirrigation is the associated decrease in agricultural chemical discharge off-site. Environmental concerns associated with subsurface drainage stem from studies that report an increase in subsurface drainage intensity results in an increase in the amount of agricultural chemicals, particularly $NO_3$–N, that are released off-site (Skaggs et al., 1994; Gilliam and Skaggs, 1986). The use of subirrigation, when compared with subsurface drainage, reduced the amount of agricultural chemicals that were released off-site (Belcher, 1990; Kanwar and Kalita, 1990; Fogiel and Belcher, 1991; Kalita et al., 1992; Kanwar et al., 1993; Fausey et al., 1995; Fisher et al., 1999; Gaynor et al., 2000).

Due to the widespread concerns about the effect of intensive agricultural practices on soil and water quality, WTM effects on soil remains a priority of research especially the soil physical properties in response to subsurface drainage or subirrigation. Few studies have been conducted to evaluate the effects of WTM on the physical properties of the soil (Chieng and Hughes-Games, 1995; Fausey et al., 1986; Hooghouldt, 1952; Lal and Fausey, 1993; Van Hoorn, 1958). Our objective was to investigate how WTM impacts soil properties relating to soil structure and the storage and movement of water within the soil, to allow for a more complete understanding of the full consequences of WTM.

## MATERIALS AND METHODS

### Description of the Study Area

This research was conducted as part of a long-term agricultural WTM experiment at the Northwest Branch of the Ohio Agricultural Research and Development Center in Wood County, Ohio (41°13′ N Lat. and 83°46′ W Long.). The elevation of the site above mean sea level is 213.4 m. The landscape was leveled by wave action on the lake plain of former postglacial Lake Maumee and has an average slope of 0 to 1%. Average annual rainfall is 840 mm with 40% of the total falling between June and September. The average annual temperature ranged between 4.6 and 16.4°C with an average wind speed of 3.7 m s$^{-1}$. The average annual solar radiation is 328 W m$^{-2}$ with maximum during May to September.

The soil at the experimental location is the Hoytville series (Fine, illitic, mesic Mollic Epiaqualfs), which is a deep very poorly drained soil with moderately slow permeability. The soil covers approximately 344 000 ha throughout northwestern Ohio, northeastern Indiana, and southeastern Michigan (www2.wcoil.com/~rfrobb/hoytville3.html [verified 30 June 2004]). This soil formed mainly from fine to moderately fine textured glacial till in the bed of former postglacial Lake Maumee.

The site chosen for this experiment did not have a subsurface drainage system in place, at least since 1954. There was evidence of a few random drain lines that existed before 1954, but these were destroyed when the present research farm was established using large management blocks with and without subsurface drainage facilities. This area had improved surface drainage and it was maintained when the new experiment was established. Subsurface drains were installed in 1991 in a pattern that divided the area into plots, each with its own outlet through a structure where WTM could be implemented. The plots are 30 by 27.5 m with drain lines spaced 6 m apart and 0.8 m below the soil surface. Each plot contained four drain lines with an additional drain line between the plots to provide hydrologic separation. A plot diagram and complete description is available in Fausey et al. (2004).

### Experimental Treatments

The experiment was originally laid-out in a 2 × 2 factorial arrangement by following a randomized complete block design with two WTM treatments and two crop phases of a corn–soybean rotation, replicated twice. Management of the plots included fall chisel plow and spring disc on the plots to be planted in soybean. The WTM treatments were (i) unrestricted subsurface drainage year round (drainage treatment); and (ii) subirrigation during the growing season to maintain a constant water table at 25 cm below the surface and unrestricted subsurface drainage during the remainder of the year (subirrigation treatment). Subirrigation began typically about Day 170 and continued for approximately 100 d. The treatment combinations were replicated twice and laid out on the existing plots. In the subirrigation plots, the water table was held at 25 cm directly above the drain line and was approximately 40 to 50 cm below the surface between the drain lines (Fig. 1). The subirrigated treatment began in the Spring 1992. Water used for subirrigation was supplied from a well and had a pH of 7.1, electrical conductivity (EC) of 1020 μS cm$^{-1}$, and soluble Ca, K, Mg, Na, and S concentrations of 114.3, 1.1, 53.2, 60.3, and 149.7 mg L$^{-1}$, respectively. Water table depths and the quality of the water below the shallow water table and in the drainage discharge were routinely monitored in each plot.

### Soil Collection, Processing, and Analysis

Soil sampling was done in the fall of 2000 after crop harvest and before any tillage took place. In each replicated plot, three sampling locations were laid out at approximately the same elevation with respect to the surface slope. These locations were midway between the drain lines and approximately 8.5 m from the north or south edge of the plots nearest to the main drain and outlet. The exact distance from the edge of the plot varied slightly to avoid wheel tracks. At each of the three sample locations within a replicated plot, six 7.6-cm diam. and six 3-cm diam. cores were collected. One large core and one small core were taken at the midpoint of each of the following depths 0 to 20, 20 to 30, 30 to 40, 40 to 50, 50 to 75, and 75 to 100 cm. The larger cores were taken with a truck-mounted hydraulically driven soil sampler and the smaller cores were taken with a hand core sampler. Each core was wrapped in plastic and returned to the laboratory. Additionally, bulk samples were taken at each sampling location by extracting a 1-m long core. Two of the three 1-m long cores were separated into increments of 0 to 20, 20 to 30, 30 to 40, 40 to 50, 50 to 75, and 75 to 100 cm. The soil core increments at each depth were composited, placed in cloth soil bags and allowed to air dry for 72 h before analysis for aggregate stabil-

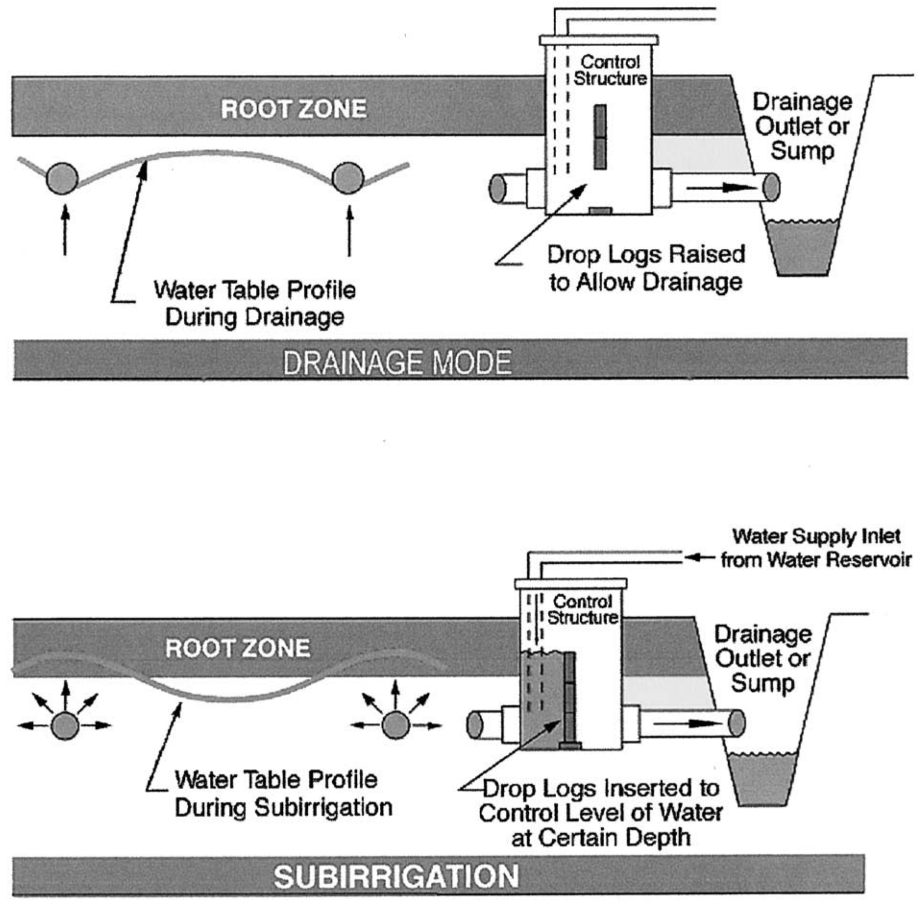


**Fig. 1. Diagram of water table management methods (Zucker and Brown, 1998).**

ity and particle size. The third 1-m long soil core from each plot was used for soil profile descriptions (data not presented).

Soil bulk density ($\rho_b$) was determined for both the 7.6- and 3-cm cores using the core method (Blake and Hartge, 1986). The total porosity ($\phi_t$) of soil was calculated from the measured values of $\rho_b$ and assumed value of soil particle density of 2.65 Mg $m^{-3}$ and was expressed as $m^3$ $m^{-3}$ of soil.

A wet sieving procedure was modified for determination of aggregate-size distribution, and aggregate stability and indices (Kemper and Rosenau, 1986). Aggregates ranging in diameter from 5000 to 8000 $\mu$m were obtained from the air-dried bulk soil, that had been broken apart by hand before air-drying, for the wet sieving procedure. Exactly 50 g of soil aggregates were placed on a set of five nested sieves with 5000-, 2000-, 1000-, 500-, and 250-$\mu$m diam. openings. The soil aggregates on the upper 5000-$\mu$m sieve were prewetted for 30 min through capillary action before they were submerged in tap water to a 3-cm depth at a rate of 30 submersions per minute for a period of 30 min. Wetting by capillary action was achieved by allowing aggregates on the 5000-$\mu$m sieve to come into contact with the water. The remainder of the nested sieves was completely submerged in water. The soil aggregate fraction retained on each sieve was then collected, dried in a forced-air oven at 105°C for 24 h and weighed. The aggregate fractions were placed in tubes and shaken with 0.5% (wt/v) sodium hexametaphosphate on a reciprocal shaker. The dispersed soil was then placed on the same size sieve it was collected on, washed with deionized water followed by drying at 105°C for 24 h and the weights were recorded for correction of primary particles. Soil aggregate indices were calculated as follows:

$$\text{Aggregate ratio} = \text{(percentage of macroaggregates)/(percentage of microaggregates)}$$

where percentage of macroaggregates are the summation of soil aggregate-size fractions larger than 250 $\mu$m and percentage of microaggregates are the summation of soil aggregate-size fractions smaller than 250 $\mu$m.

$$\text{Mean weight diameter (MWD)} = \Sigma x_i y_i$$

where $x_i$ is the mean diameter of the soil aggregate size (mm) fractions and $y_i$ is the proportion of each aggregate size with respect to the total sample weight.

$$\text{Geometric mean diameter (GMD)} = \exp(\Sigma w_i \ln x_i)/\Sigma w_i$$

where $w_i$ is the weight of the aggregates of each fraction (g) and $x_i$ is the natural logarithm of the mean diameter of the soil aggregate sizes.

$$\text{Percentage of aggregate stability} = (x_i/y_i)100$$

Where $x_i$ is the weight of soil remaining on the sieves and $y_i$ is the total weight of the sample.

Penetration resistance was measured using a cone penetrometer equipped with a data logger. The cone penetrometer was pushed into the soil to measure pressure every 15 cm to a depth of 45 cm. Readings were taken midway between the drain lines at approximately 10 m from the edge of the plots. Three readings were taken at each of the three sampling locations described previously, for nine readings per plot. The readings were taken in both spring and fall seasons. The spring readings were taken on 9 Apr. 2001 after fall tillage and the fall readings were taken 8 Nov. 2001 before fall tillage. Soil moisture samples were also collected to confirm that any differences between WTM treatments found were due to penetration resistance and not moisture content differences.

Volumetric moisture contents at different matric potentials were determined using the 3-cm soil cores. A tension table was used to determine the soil moisture content at −0.00015, −0.003, and −0.006 MPa. A pressure plate apparatus was used to determine the soil moisture content at −0.03, −0.1, −0.3, and −1.5 MPa (Klute, 1986). The available water capacity of soil was calculated from the difference in volumetric moisture content of soil at −0.03 and −1.5 MPa.

Soil particle-size analysis was performed by the hydrometer method after removing organic matter with 30% (wt/wt) $H_2O_2$ followed by dispersion of soil with sodium hexametaphosphate (Gee and Bauder, 1986).

### Statistical Analysis of Data

Differences in soil properties in response to the effects of WTM and depth of soil were analyzed using an Analysis of Variance model procedure (SAS Institute, 2001). Treatment means and interactions were separated by a LSD multiple comparison procedure at $p \leq 0.05$. The differences among treatment means at $p \leq 0.10$ were considered trends.

## RESULTS

### Basic Soil Characteristics

Mean and standard deviation of a basic soil analysis of the soil samples from the 0- to 1-m depth at this site are as follows—a pH of 7.4 ± 0.1, an electrical conductivity of 235 ± 55 μS cm$^{-1}$, a cation exchange capacity of 160 ± 1.2 mmol (+) kg$^{-1}$, a base exchange saturation of 71.4 ± 3.4%, a total amount of C of 17.4 ± 0.2 g kg$^{-1}$, sand equal to 113.3 ± 9.2 g kg$^{-1}$, silt equal to 372.3 ± 3.9 g kg$^{-1}$, clay equal to 509.8 ± 8.2 g kg$^{-1}$, a liquid limit of 0.44 ± 0.005, a plastic limit of 0.27 ± 0.01, and a sticky point of 0.37 ± 0.01.

### Aggregate-Size Fraction Distribution and Stability of Soil

Aggregate-size fraction distribution, percentage of aggregate stability, and aggregate ratios are indices that varied significantly in response to WTM and depth of soil (Tables 1–2 and Fig. 2). When comparing the effect of WTM treatments, the subirrigated soil had a smaller percentage of 2000- to 5000- and 1000- to 2000-μm aggregate-size fractions but greater percentage of 250- to 500-μm size fraction than the drained soil (Table 1). Among the macroaggregate-size fractions, the greatest percentages of stable aggregates were in the 2000- to 5000- and 1000- to 2000-μm size fractions in the drained soils compared with the 1000- to 2000- and 500- to 1000-μm size fraction in the subirrigated soils. In addition, the subirrigated soil contained a significantly greater percentage of microaggregates than the drained soil. On average, the aggregate ratio (i.e., percentage of macroaggregates/percentage of microaggregates) was smaller in the subirrigated soil than the drained soil (Table 1). When comparing the effect of WTM treatments, there was a significant difference in aggregate stability between the subirrigation treatment and the drainage treatment (Fig. 2). Soil depth also had a significant main effect on aggregate stability of the soil. The subirrigated treatment had a significantly lower aggregate stability in the sampling depths of 40 to 50 and 50 to 75 cm with the trend continuing into the 20- to 30- and 30- to 40-cm depths. In the 0- to 20-cm depth, the drained treatment

**Table 2. Mean weight diameter (MWD) and geometric mean diameter (GMD) of soil.**

| | Depth of soil, cm | | | | | | |
|---|---|---|---|---|---|---|---|
| WTM† | 0–20 | 20–30 | 30–40 | 40–50 | 50–75 | 75–100 | Mean |
| | | | | MWD, mm | | | |
| Drainage | 1.45Ba‡ | 1.47Ba | 1.65Aa | 1.77Aa | 1.46Ba | 0.65Ca | 1.41a |
| Subirrigation | 1.77Ab | 1.50Ba | 1.43Bb | 1.49Bb | 1.02Cb | 0.67Da | 1.31b |
| Mean | 1.61A | 1.49A | 1.54A | 1.63A | 1.24B | 0.66C | |
| | | | | GMD, mm | | | |
| Drainage | 1.64ABb | 1.56Ba | 1.66ABa | 1.76Aa | 1.51Ba | 1.03Ca | 1.53a§ |
| Subirrigation | 1.89Aa | 1.59Ba | 1.48Bb | 1.54Bb | 1.19Cb | 1.02Da | 1.45a§ |
| Mean | 1.77A | 1.58B | 1.57B | 1.65AB | 1.35C | 1.03D | |

† Water table management.
‡ Means followed by the different upper case letters in the same row were significantly different at $p < 0.05$. Means followed by the different lower case letters in the same column were significantly different at the $p < 0.05$.
§ Indicates trends ($p < 0.10$).

**Table 1. Soil aggregate-size distribution and aggregate ratios in response to water table management (WTM) and soil depth.**

| | | Aggregate size, μm | | | | | | |
|---|---|---|---|---|---|---|---|---|
| WTM | Soil depth | >5000 | 2000–5000 | 1000–2000 | 500–1000 | 250–500 | <250 | Aggregate ratio |
| | cm | % | | | | | | |
| Drainage | 0–20 | 10.4a† | 18.7d | 16.2d | 16.5d | 10.0bc | 28.3b | 2.54d |
| | 20–30 | 8.0b | 21.5c | 20.5c | 18.7b | 10.3b | 20.9c | 3.78c |
| | 30–40 | 8.7ab | 24.1b | 23.7b | 18.3bc | 8.7d | 16.4de | 5.09b |
| | 40–50 | 9.2ab | 27.4a | 24.7a | 18.1bc | 7.6e | 13.1e | 6.64a |
| | 50–75 | 6.7c | 22.6c | 24.2ab | 21.6a | 9.6c | 15.1de | 5.61ab |
| | 75–100 | 2.0d | 9.4e | 12.1e | 17.7c | 14.0a | 44.7a | 1.23e |
| Mean | | 7.5Da‡ | 20.6Ba | 20.3Ba | 18.5Ca | 10.0Db | 23.1Ab | 4.32a |
| Subirrigation | 0–20 | 16.8a | 17.5c | 15.2d | 15.0f | 9.5de | 25.8b | 2.87b |
| | 20–30 | 10.1b | 19.6b | 18.8c | 17.8d | 11.0b | 22.7b | 3.41b |
| | 30–40 | 6.2c | 20.8b | 24.7a | 22.5b | 10.0cd | 17.8c | 4.73a |
| | 40–50 | 6.2c | 23.2a | 24.1a | 20.3c | 9.3e | 16.8c | 4.95a |
| | 50–75 | 1.9d | 16.5c | 20.7b | 24.2a | 12.8a | 23.8b | 3.20b |
| | 75–100 | 1.8d | 8.7d | 10.4e | 16.2e | 12.2a | 50.6a | 0.97c |
| Mean | | 7.2Ea | 17.7Cb | 19.0Bb | 19.0Ba | 10.8Da | 26.3Aa | 3.47b |

† Differences ($p < 0.05$) in aggregate-size distribution and aggregate ratio due to depth within each treatment are shown by different lower case letters in the columns.
‡ Mean followed by the different uppercase letters in the same row were significantly different at $p < 0.05$.

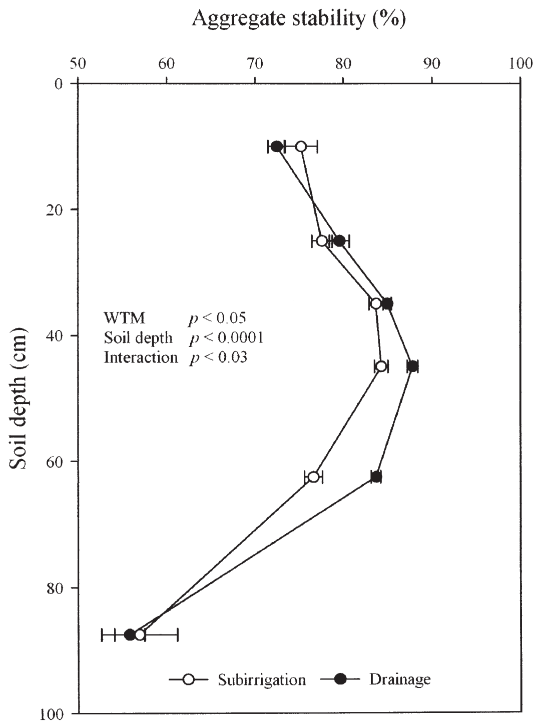


**Fig. 2. Aggregate stability with soil depth.**

had a lower aggregate stability than the subirrigated treatment (Fig. 2).

The MWD of the soil aggregates in the subirrigated treatment was significantly smaller (about 8%) compared with the drainage treatment over all soil depths (Table 2). The MWD of the soil aggregates in the subirrigated treatment was smaller at depths of 30 to 40, 40 to 50, and 50 to 75 cm but larger at the 0- to 20-cm depth than in the drainage treatment (Table 2). When comparing the effect of soil depth across both treatments, the MWD of aggregates was larger at 40- to 50-, 0- to 20-, 30- to 40-, and 20- to 30-cm depths, respectively than at other depths of soil. Likewise, there was a trend in the differences in GMD of aggregates with the subirrigated treatment having a smaller mean GMD than the drained treatment (Table 2). A significant difference in GMD of soil aggregates was found between WTM treatments at each of the following depths 0 to 20, 30 to 40, 40 to 50, and 50 to 75 cm. When comparing the effect of soil depth across treatments, the GMD of aggregates was largest at 0- to 20- and 40- to 50-cm depths of soil (Table 2).

Soil physical properties are often affected by altering the water table. Differences found when comparing the WTM treatments may have been the result of alteration of the air–water–soil matrix dynamics, resulting in the subirrigated soils not forming large stable aggregates as the drained soil did. Due to water saturation of the soil profile below the 30- to 50-cm depth, the subirrigated soils were not able to dry out and shrink; therefore, the soil microaggregates and primary particles could not bind together to form macroaggregates. Additionally, the temporal water saturation of the soil may have caused slaking and the breakdown of macroaggregates through entrapped air escaping and thick water films. The ultimate result is fewer macroaggregates with an associated increase in microaggregates, smaller MWD and GWD of the soil aggregates, and subsequent lower soil aggregate stability within the subirrigated treatment. This is shown in our results with smaller MWD and GMD of aggregates below the 30-cm depth in the subirrigated treatment compared with the drainage treatment. Van Hoorn (1958) reported similar findings when maintaining the water table at 40 cm below the soil surface. The MWD of soil aggregates was greater for the drainage treatment, indicating a greater number of large aggregates. The GMD expresses the dominant aggregate-size class of the soil and was trending toward the subirrigated treatment having a smaller GMD than the drainage treatment. If the MWD and GMD change, it means soil macroporosity also changes. Hooghouldt (1952) reported that where the water table was maintained at 40, 60, 90, 120, and 150 cm below the surface during the growing season there was no significant variation in soil physical properties for 5 yr following installation of the drainage system. However, after 5 yr distinct differences were reported for the surface layers of the soil with a water table maintained at 40 cm below the soil surface. The soil was reported to be wetter making tillage more difficult with a greater number of large size clods than macroaggregates at the soil surface (Van Hoorn, 1958).

In the drained soil, microaggregates and primary particles may have pulled into close contact with each other in response to drainage of excess water thus increasing the number of contacts among soil primary particles and microaggregates to enhance macroaggregation. This phenomenon is more pronounced in clay soils than in silty or sandy soils (Becher, 1998). The result is greater aggregate stability with a dominance of macroaggregate-size fraction that is determined by the intensity and duration of the soil drying-wetting cycles in the drained soils (Becher, 1998). The stability of soil surface aggregates relies on soil organic matter, as one of the cementing agents, enabling them to withstand rapid wetting and drying of soil (Hernanz et al., 2002). Draining the soil could have enhanced the chemical oxidation of soil labile organic matter followed by deterioration in macroaggregate stability of surface soil. Relatively lower aggregate stability of surface soils (0–20 cm) under the drainage treatment can be attributed to the oxidation of labile organic matter with an effect of increased hydrophilic character of the aggregates, thereby enhancing their disintegration upon being wetted (Horn et al., 1994).

## Bulk Density, Total Porosity, and Penetration Resistance of Soil

Averaged across soil depths, WTM significantly affected the bulk density ($\rho_b$) and total porosity ($\phi_t$) of the soil (Fig. 3 and 4). The drained treatment exhibited greater $\rho_b$ values at all depths, however, the differences were not significant at the 30- to 40- and 75- to 100-cm depths (Fig. 3). Most of the $\rho_b$ values observed were within the 1.28- to 1.58-Mg m$^{-3}$ range for both WTM treatments. On average, the $\rho_b$ significantly increased

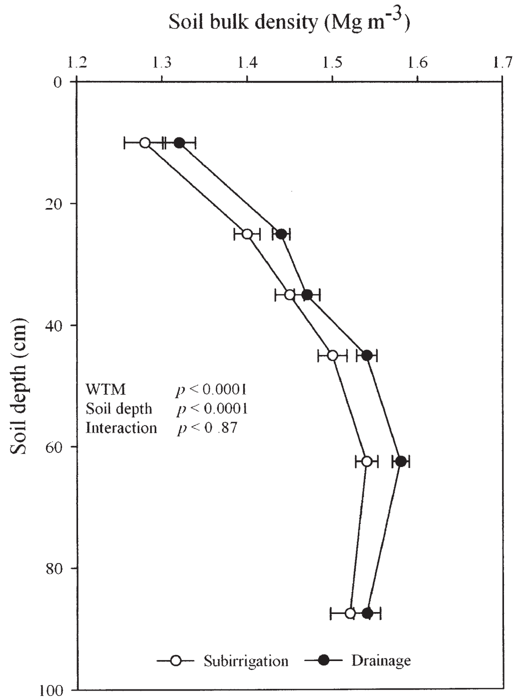


**Fig. 3. Soil bulk density with depth.**

with progressive soil depth. Greater $\rho_b$ was measured at depth below 40 cm compared with $\rho_b$ values measured at surface depth. This could be the result of the tillage practices. The $\phi_t$ for the two WTM treatments was significantly different, with $\phi_t$ being slightly greater in the subirrigated treatment compared with the drained treatment (Fig. 4). Significantly smaller $\phi_t$ values were observed with progressive depth of the soil and the effect

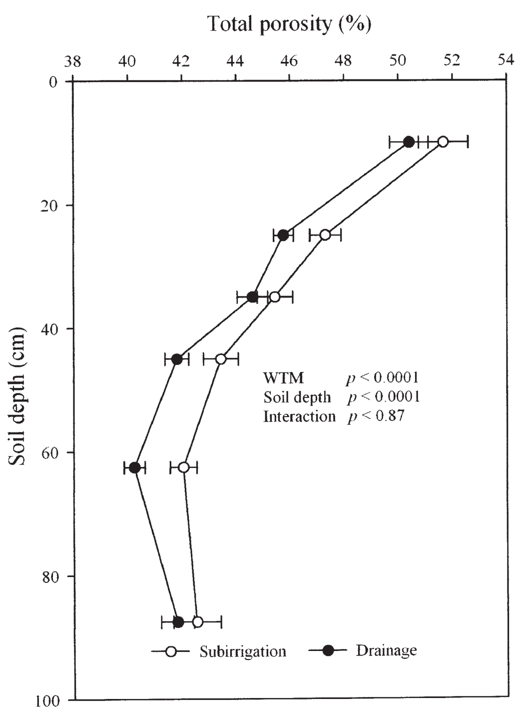


**Fig. 4. Total porosity with depth.**

**Table 3. Temporal effects of water table management treatments (WTM) and soil depths on penetration resistance (MPa).**

| | Depth of soil, cm | | | | |
|---|---|---|---|---|---|
| **Experimental variables** | **0** | **15** | **30** | **45** | **Mean** |
| **WTM** | | | | | |
| **Drainage** | **0.49a†** | **1.02a** | **1.56a** | **1.83a** | **1.23a** |
| **Subirrigation** | **0.53a** | **0.99a** | **1.32b** | **1.70B** | **1.12b** |
| **Soil depth** | **0.51D‡** | **1.00C** | **1.44B** | **0.77A** | |
| **Simple effects of date** | | | | | |
| **04/9/01** | **0.19b** | **0.75b** | **1.28b** | **1.69b** | **0.98b** |
| **10/8/01** | **0.84a** | **1.26a** | **1.60a** | **1.78a** | **1.37a** |
| | | | **Interactive effects** | | |
| **Drainage** | | | | | |
| **04/9/01** | **0.19Db** | **0.73Cb** | **1.37Bb** | **1.82Aa** | **1.03b** |
| **10/8/01** | **0.79Da** | **1.31Ca** | **1.76Ba** | **1.85Aa** | **1.43a** |
| **Subirrigation** | | | | | |
| **04/9/01** | **0.19Db** | **0.77Cb** | **1.19Bb** | **1.56Ab** | **0.92b** |
| **10/8/01** | **0.88Da** | **1.21Ca** | **1.45Ba** | **1.70Aa** | **1.31a** |

**† Means followed by different lower case letters in the same column were significantly different at $p < 0.05$.**
**‡ Means followed by the different upper case letters in the same row were significantly different at $p < 0.05$.**

was more pronounced in the drained treatment as compared with the subirrigated treatment.

Soil penetration resistance was significantly different in response to WTM, sampling date, and soil depths (Table 3). On average, the drained treatment exhibited more resistance to penetration than the subirrigated treatment. The effect was more pronounced at the 30- and 45-cm depths of soil. When comparing the effect of soil depth, the highest penetration resistance was measured at the 15- and 30-cm depths of soil. The fall-sampled soil had significantly greater penetration resistance than spring sampled soil and the effect was consistent with progressive depths of soil. The difference reported between the fall and spring readings may be due to the fall samples being taken before fall tillage and the spring samples being taken after fall tillage. Soil penetration resistance data measured in spring showed that the subirrigated treatment has a significantly lower penetration resistance than the drainage treatment at a depth of 45 cm. Similarly, the subirrigated treatment had a tendency for lower resistance to penetration in the spring and fall at 30 cm and fall at 45 cm, although significant differences were not found. Soil moisture measurements taken in conjunction with the penetration readings indicate no significant moisture content differences between the treatments.

The $\rho_b$ was significantly less in the subirrigated treatment while the $\phi_t$ was significantly greater. These results could possibly be due to slaking and dispersion of the soil macroaggregates under subirrigated conditions compared with continuously drained conditions. Slaking occurs when macroaggregates are not able to withstand the pressures of entrapped air in capillaries or the pressure due to swelling in response to close contact with water (Tisdall and Oades, 1982). When soil aggregates collapse and slake during a continuous wetting front, they form a slick dispersed layer over time. As a result, the $\phi_t$ increases with an associated decrease in $\rho_b$ and penetration resistance. In this research, the effect was more pronounced in and around the subirrigated water table zone. Continuous drainage, on the other hand, had a tendency to pack soils at subsurface depths. Therefore, the $\rho_b$ in the drainage treatment below the 30- to 40-cm depth was greater with an associated lower $\phi_t$. Lower $\phi_t$ of well-drained soil suggests that it would be far more likely to be dominated by macropores over micropores.

The lower values for penetration resistance measured in the subirrigated treatment are possibly due to weaker aggregate stability, smaller MWD and GMD of aggregates, and greater micropores in soil. Ponnamperuma (1984) suggested that structural deterioration in flooded soils is caused by several factors such as aggregate breakdown due to dilution of soil solution, pressure of entrapped air, stresses caused by uneven swelling, and destruction of cementing agents under reducing conditions. These findings supported that the wetter the soil, the weaker the aggregates, and the lower the resistance to penetration (Becher, 1998).

## Volumetric Water Content of Soil

There was an apparent difference in the volumetric water content of soil at different matric potentials and available water capacity (AWC) in response to WTM and soil depth (Table 4 and Fig. 5). On average, the subirrigated soil held significantly more moisture than the drained soil at all matric potentials except −0.00015 and −1.5 MPa (wilting point). Sampling depth also had a significant effect on the volumetric moisture content of the soil. A greater volume of soil moisture was measured at all energy levels in the 30- to 40-cm depth with the exception of the moisture content at the wilting point. As a result, the subirrigated treatment had greater AWC (about 11%) than the drainage treatment (Fig. 5). When comparing the effect of soil depth, the AWC was greater at 20- to 30- and 30- to 40-cm depths than at 0- to 20-, 40- to 50-, 50- to 75- and 75- to 100-cm depths. The AWC decreased with progressive increase in soil depth beyond 40 cm.

The significantly greater volumetric moisture content of the subirrigated soil supported our results that the subirrigated treatment had more porosity with a pore-size distribution shifted toward micropores from macropores compared with the drainage treatment. The shift in the pore-size distribution from a greater number of macropores to a greater number of micropores is clearly illustrated in the soil moisture release characteristics at different matric potentials (Table 4). Similar results were reported by Van Hoorn (1958) after 5 yr of maintaining the ground water at 40 cm below the soil surface. A decrease in the percentage of macropores and an increase in the percentage of micropores directly above the ground water level were reported by Van Hoorn (1958). With a fewer number of macroaggregates and interaggregate pores as a result of soil structural slaking and a lack of microaggregate bonding, the percentage of macropores in the subirrigated treatment was less than in the drainage treatment.

Chieng and Hughes-Games (1995) reported a significant decrease in drainable porosity (macropores) with subirrigation. Lower macroporosity of our subirrigated soils is possibly due to slaking of macroaggregates followed by dispersion of silt and clay particles from long-term use of slightly saline ground water for subirrigation. With lower macroporosity, the moisture holding capacity of soil was affected substantially. A possible theory that may explain our results is when subsurface soil horizons are nearly saturated under subirrigation; the air-filled pores are under pressure that may cause the breakdown of macroaggregates as the air escaped (air slaking). Slaking would reduce the number of air-filled macroaggregates followed by a dominance of micro- and small interaggregate pores in soil. These events may have been responsible for the greater volume of water held in subirrigated soil at matric potentials less than −5 kPa. Results of a study on Toledo silty clay showed an increase in air filled porosity of soils with subsurface drainage and both subsurface and surface drainage when

**Table 4. Volumetric moisture content at various matric potentials in response to water table management (WTM) and soil depths.**

| | Matric potential, MPa | | | | | | |
|---|---|---|---|---|---|---|---|
| Experimental treatments | −0.00015 | −0.003 | −0.006 | −0.03 | −0.1 | −0.3 | −1.5 |
| WTM | | | | | | | |
| Drainage | 0.54a† | 0.51b | 0.49b | 0.46b | 0.43b | 0.40b | 0.24a |
| Subirrigation | 0.55a | 0.53a | 0.51a | 0.48a | 0.46a | 0.43a | 0.24a |
| Soil depth, cm | | | | | | | |
| 0–20 | 0.55ab | 0.49d | 0.47c | 0.44c | 0.41d | 0.38d | 0.21b |
| 20–30 | 0.56a | 0.53ab | 0.52a | 0.48ab | 0.46ab | 0.43ab | 0.24a |
| 30–40 | 0.56a | 0.54a | 0.52a | 0.49a | 0.47a | 0.44a | 0.24a |
| 40–50 | 0.55ab | 0.52abc | 0.51ab | 0.48ab | 0.46ab | 0.42ab | 0.25a |
| 50–75 | 0.53b | 0.51bcd | 0.50b | 0.47b | 0.45bc | 0.41bc | 0.26a |
| 75–100 | 0.53b | 0.50cd | 0.49bc | 0.45c | 0.43c | 0.40c | 0.25a |

† Means followed by different lower case letters in the same column were significantly different at $p < 0.05$.

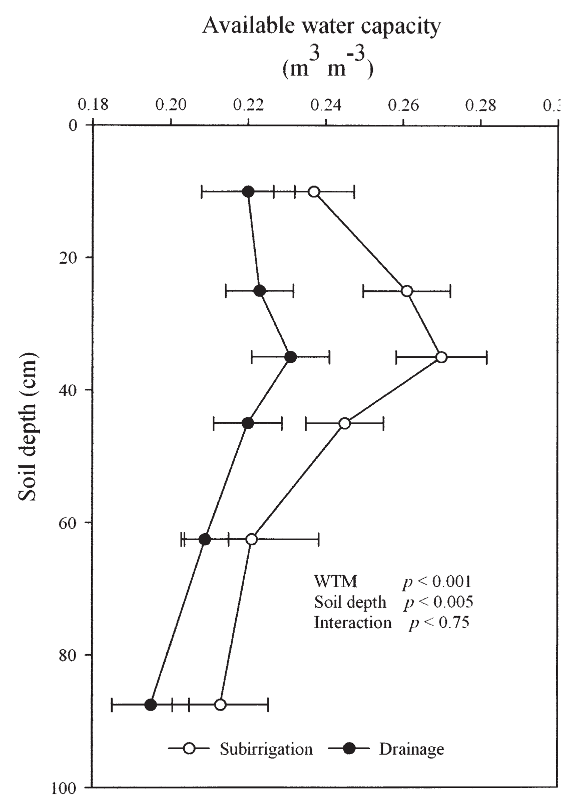


**Fig. 5. Available water capacity with depth.**

**Table 5. Soil particle-size distribution in response to water table management (WTM).**

| WTM | Soil depth, cm 0–20 | 20–30 | 30–40 | 40–50 | 50–75 | 75–100 | Mean |
|---|---|---|---|---|---|---|---|
| | | | | Sand, g kg$^{-1}$ | | | |
| Drainage | 123ABa† | 107Ba | 136Aa | 132Aa | 75Ca | 124ABa | 118a |
| Subirrigation | 134Aa | 99Ba | 124Aa | 121Aa | 76Ca | 94BCb | 108a |
| Mean | 128AB | 103C | 130A | 127AB | 76D | 109BC | |
| | | | | Silt, g kg$^{-1}$ | | | |
| Drainage | 376ABa | 387Aa | 357Ba | 376ABa | 396Aa | 395Aa | 381a |
| Subirrigation | 376Aa | 350BCb | 331BCb | 340Cb | 384Aa | 385Aa | 360b |
| Mean | 372AB | 369AB | 344C | 358BC | 390A | 390A | |
| | | | | Clay, g kg$^{-1}$ | | | |
| Drainage | 501Ba | 505Bb | 506ABb | 491Bb | 529Aa | 469Cb | 500b |
| Subirrigation | 499Ca | 534ABa | 545Aa | 539ABa | 540ABa | 521BCa | 530a |
| Mean | 500BC | 519AB | 526A | 515ABC | 534A | 495C | |

† Means followed by different lower case letters in the same column were significantly different at $p < 0.05$. Means followed by the different upper case letters in the same row were significantly different at $p < 0.05$.

compared with soils with no drainage or surface drainage alone (Hundal et al., 1976). An increase in drainable porosity of the soil in the drainage treatment suggests a greater portion of large pores with more water stable macroaggregates within the soil (Hundal et al., 1976).

## Particle-Size Distribution of Soil

A comparison of WTM treatments indicates the subirrigated treatment had a greater mass of clay at depths 20 to 30, 30 to 40, 40 to 50, and 75 to 100 cm than the drainage treatment (Table 5). An opposite trend is found in the results of the silt size particles with the drainage treatment having a greater mass of silt at depths 20 to 30, 30 to 40, and 40 to 50 cm than the subirrigated treatment. There are two possible theories to explain the differences found between the WTM treatments. The first being the more stable aggregates, as reported in the aggregates stability test, in the drained treatment did not fully disperse with the sodium hexametaphosphate treatment. Microaggregates that are not fully dispersed into their component parts may appear to be silt- sized particles in the analysis thus artificially inflating the silt values and decreasing the clay values. The second possible explanation is that the drained soils experience greater clay-sized particle losses as sediment in the drainage water than the subirrigated soils. Schwab et al. (1985) reported sediment losses in drainage water averaged 1439.2 kg ha$^{-1}$ per year in clay soils. Although it is also possible that the differences in the particle-size distribution between the treatments is the result of innate differences and not the effect of the treatments.

## CONCLUSIONS

Differences are found in the soil physical properties under the two WTM treatments tested in this research. Evidence of lower aggregate stability and associated properties in the subirrigated soils is found in the measurements of aggregate stability, MWD and GMD of soil aggregates, penetration resistance, and the soil moisture release characteristics. A significantly lower aggregate stability was found in the subirrigated treatment at the 40- to 50- and the 50- to 75-cm depths and the trend continued to the upper depths of the soil as well. In addition, subirrigated soils had a lower MWD and GMD of aggregates at depths of 30 to 40, 40 to 50, and 50 to 75 cm. Results from the penetration resistance showed the subirrigated soils had a lower penetration resistance than the soils under the drainage treatment, suggesting the aggregates in the subirrigated soil may be less stable. The greater volumetric moisture content for the subirrigated treatment indicated the presence of fewer macropores than the drainage treatment. This may result from fewer macroaggregates in the soil that creates macropores. More research is needed to determine if the differences in soil aggregate properties will impact the long-term sustainability of WTM by subirrigation. It is unclear at this point if the differences found between the WTM treatments are the result of a decrease in aggregation in the subirrigated soil or an increase in aggregation in the drained soil.

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